2013

PRELUDE TO SEVEN SLOTS: FILLING AND SUBSEQUENT MODIFICATION OF SEVEN BROAD CANYONS IN THE NAVAJO SANDSTONE, SOUTH-CENTRAL UTAH

David B. Loope
University of Nebraska, Lincoln, dloope1@unl.edu

Ronald J. Goble
University of Nebraska-Lincoln, rgoble2@unl.edu

Joel P. L. Johnson
The University of Texas at Austin

PRELUDE TO SEVEN SLOTS: FILLING AND SUBSEQUENT MODIFICATION OF SEVEN BROAD CANYONS IN THE NAVAJO SANDSTONE, SOUTH-CENTRAL UTAH

by

David B. Loope[1], Ronald J. Goble[1], and Joel P. L. Johnson[2]

ABSTRACT

Within a four square kilometer portion of Grand Staircase-Escalante National Monument, seven distinct slot canyons cut the Jurassic Navajo Sandstone. Four of the slots developed along separate reaches of a trunk stream (Dry Fork of Coyote Gulch), and three (including canyons locally known as "Peekaboo" and "Spooky") are at the distal ends of south-flowing tributary drainages. All these slot canyons are examples of epigenetic gorges—bedrock channel reaches shifted laterally from previous reach locations. The previous channels became filled with alluvium, allowing active channels to shift laterally in places and to subsequently re-incise through bedrock elsewhere. New evidence, based on optically stimulated luminescence (OSL) ages, indicates that this thick alluvium started to fill broad, pre-existing, bedrock canyons before 55,000 years ago, and that filling continued until at least 48,000 years ago.

Streams start to fill their channels when sediment supply increases relative to stream power. The following conditions favored alluviation in the study area: (1) a cooler, wetter climate increased the rate of mass wasting along the Straight Cliffs (the headwaters of Dry Fork) and the rate of weathering of the broad outcrops of Navajo and Entrada Sandstone; (2) windier conditions increased the amount of eolian sand transport, perhaps destabilizing dunes and moving their stored sediment into stream channels; and (3) southward migration of the jet stream diminished the frequency and severity of convective storms. We hypothesize that a subsequent increase in the frequency of intense runoff events after 48 ka, combined with the diversion of flow over steep but unchannelized bedrock surfaces, led to a brief and unusual episode of rapid canyon cutting. This work illustrates a specific mechanism by which climate change can induce river incision, and conversely how information on climate may be recorded in the morphology of erosional landscapes.

INTRODUCTION

Carved into thick sandstones and limestones by flash floods, slot canyons of the Colorado Plateau are beautiful, dangerous, and popular. The slot canyons of our study area (figures 1, 2) are cut into the Jurassic Navajo Sandstone and lie along Dry Fork—a tributary of the Escalante River. The drainage area of Dry Fork above the confluence with Spooky Slot (figure 2) is 65 square kilometers (Wohl and others, 1999). The Straight Cliffs escarpment, the northeast margin of the Kaiparowits Plateau (figure 2A), is 2200 meters above sea level and forms the southwestern drainage divide of Dry Fork, which lies 700 meters below that escarpment. Peekaboo Slot and Spooky Slot (figure 2) have drainage areas of less than 10 square kilometers. Even in these small drainages, runoff from bedrock during heavy rainstorms generates violent floods. From Dry Fork slot (trunk slot #1 in figure 2), Wohl and others (1999) reported a silt line left by floodwaters that was positioned 4.5 meters above the streambed.

These slot canyons are among the most-visited backcountry sites in Grand Staircase-Escalante National Monument, and hikers sometimes become disoriented by this landscape with "too many canyons." With only a few hours of walking, it is possible to see six different, broad canyons without a sizable, active stream as well as six short, narrow slots that show clear evidence of large-scale, recent flooding. On maps and aerial photos, it becomes clear that each of these six slot canyons is paired with a broad, abandoned canyon (figures 2C, 3, 4, 5). A seventh slot canyon (just east of Brimstone Canyon, figures 2C, 4), is an "orphan." It is no longer connected to the stream that cut it, and its adjacent "parent" canyon has no thick alluvium and floods regularly.

Van Williams (1984) of the U.S. Geological Survey was the first to study these canyons. He recognized two

[1]*Department of Earth & Atmospheric Sciences, University of Nebraska, Lincoln, NE*

[2]*The University of Texas at Austin, Department of Geological Sciences, Jackson School of Geosciences, Austin, TX*

Loope, D.B., Goble, R.J., and Johnson, J.P.L., 2014, Prelude to seven slots—filling and subsequent modification of seven broad canyons in the Navajo Sandstone, south-central Utah, in *MacLean, J.S., Biek, R.F., and Huntoon, J.E., editors, Geology of Utah's Far South: Utah Geological Association Publication 43, p. 11–24.*

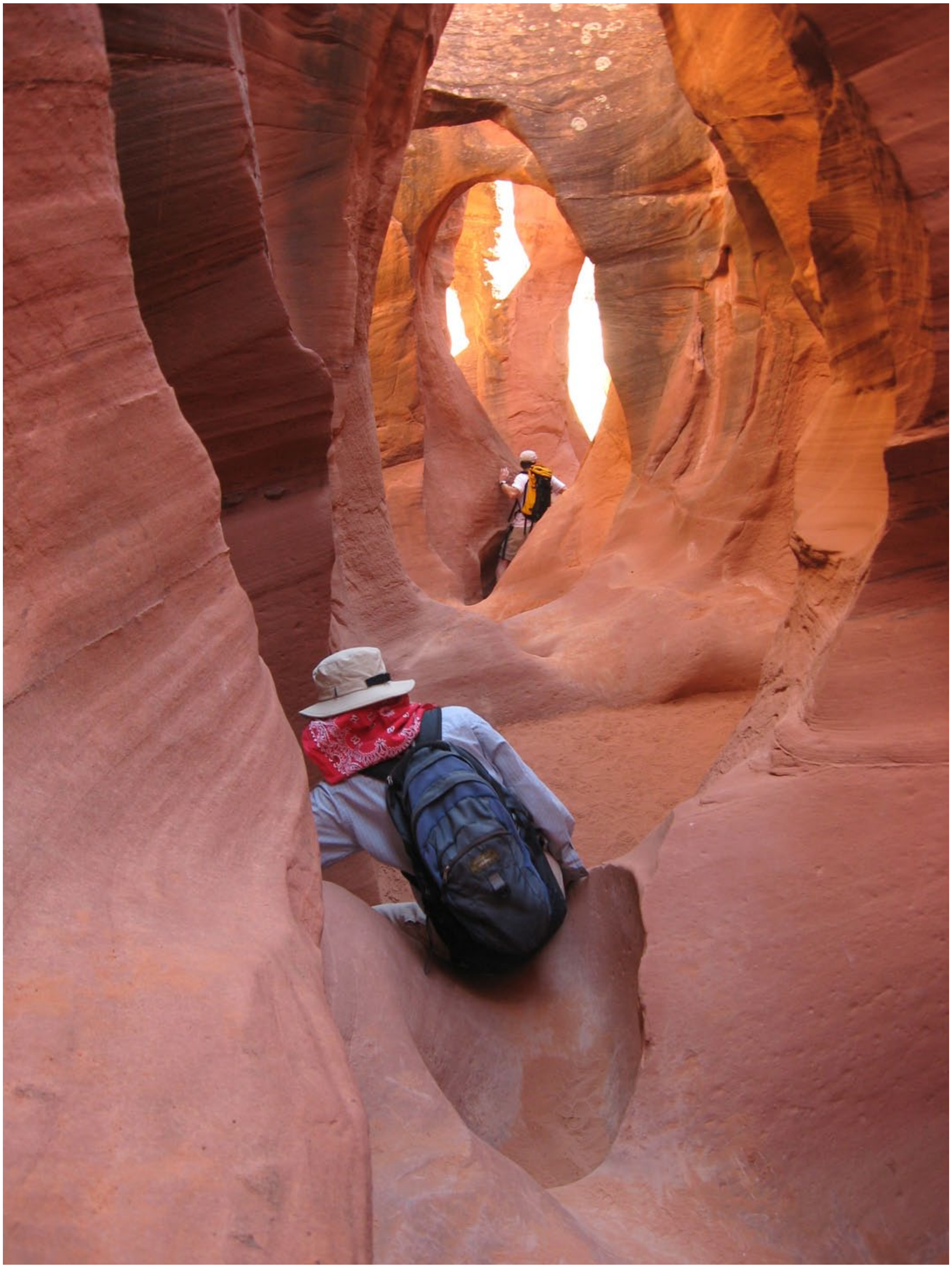

Figure 1. *Hikers in Peekaboo Slot. Photo by Jim Elder.*

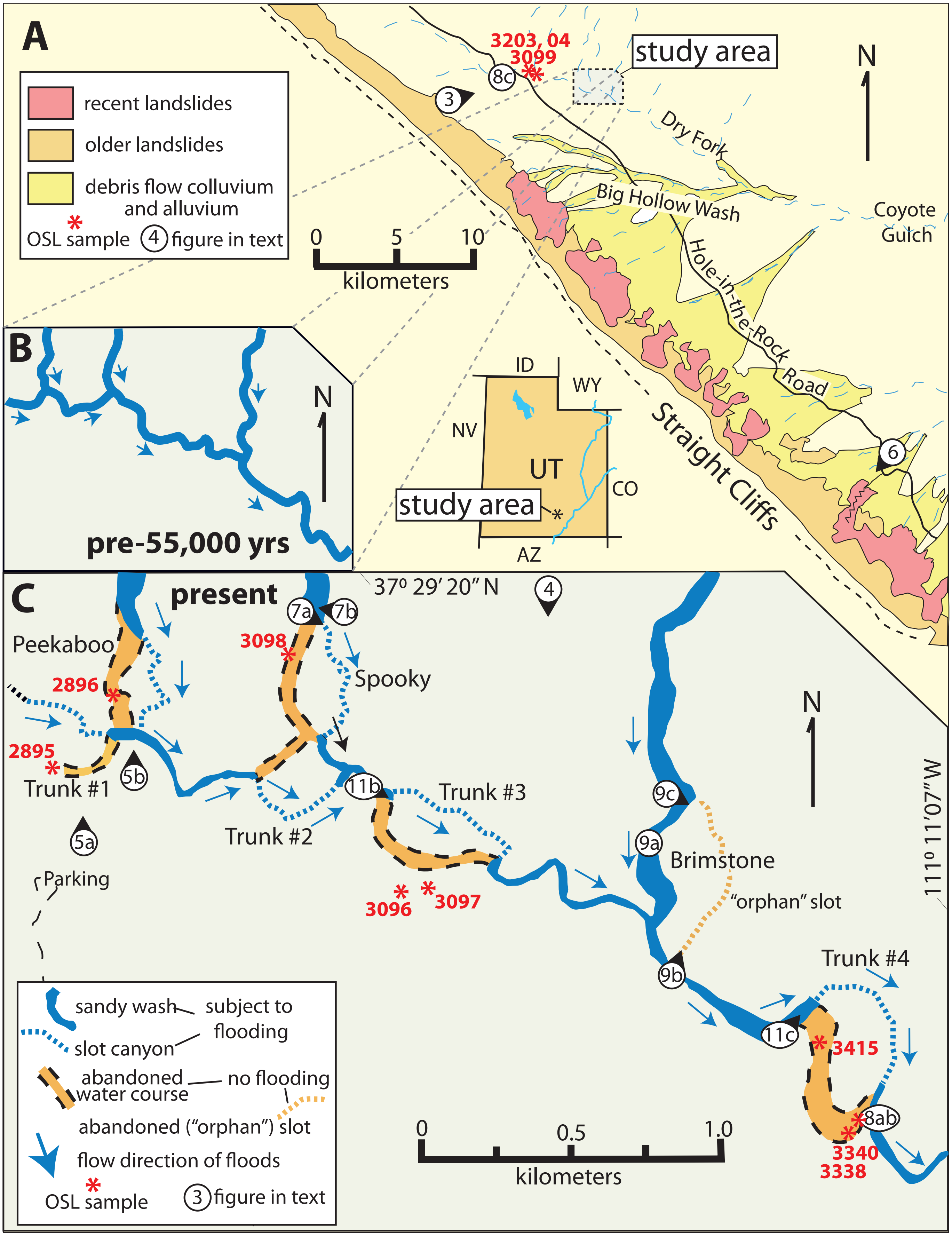

Figure 2. Maps of the study area, showing locations of sample sites and figures. A. Surficial geologic map of Williams (1985), showing setting of study area. B. Configuration of drainages prior to alluviation. C. Present configuration of slot canyons and abandoned water-courses.

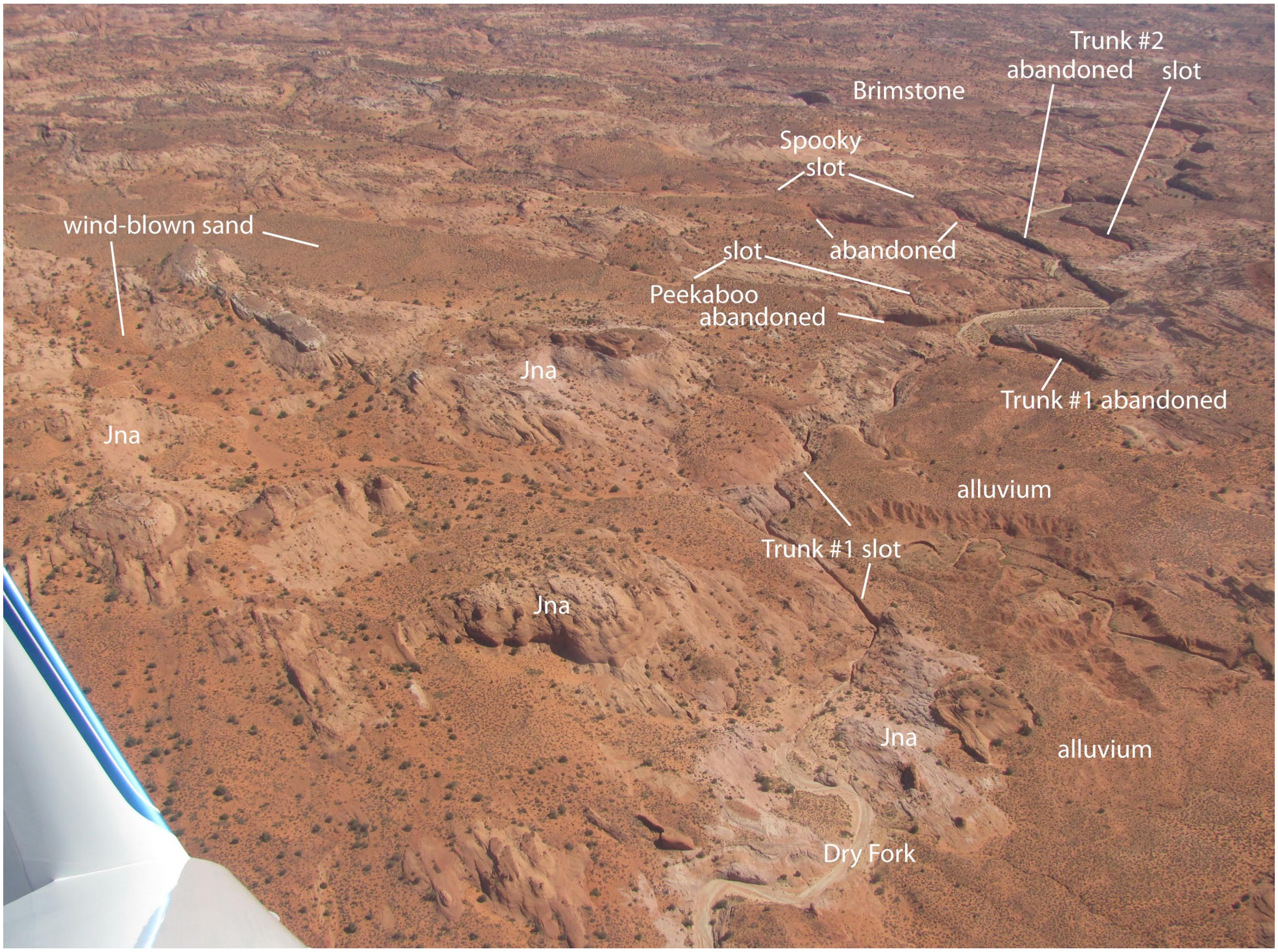

Figure 3. *Air photo looking downstream (eastward) above Dry Fork, with south-flowing tributaries: Peekaboo, Spooky, and Brimstone. Note pairings of slot canyons and abandoned, sand-filled canyons, and extent of remaining alluvium, mantles of wind-blown sand, and the sea of naked Navajo Sandstone bedrock (Jna).*

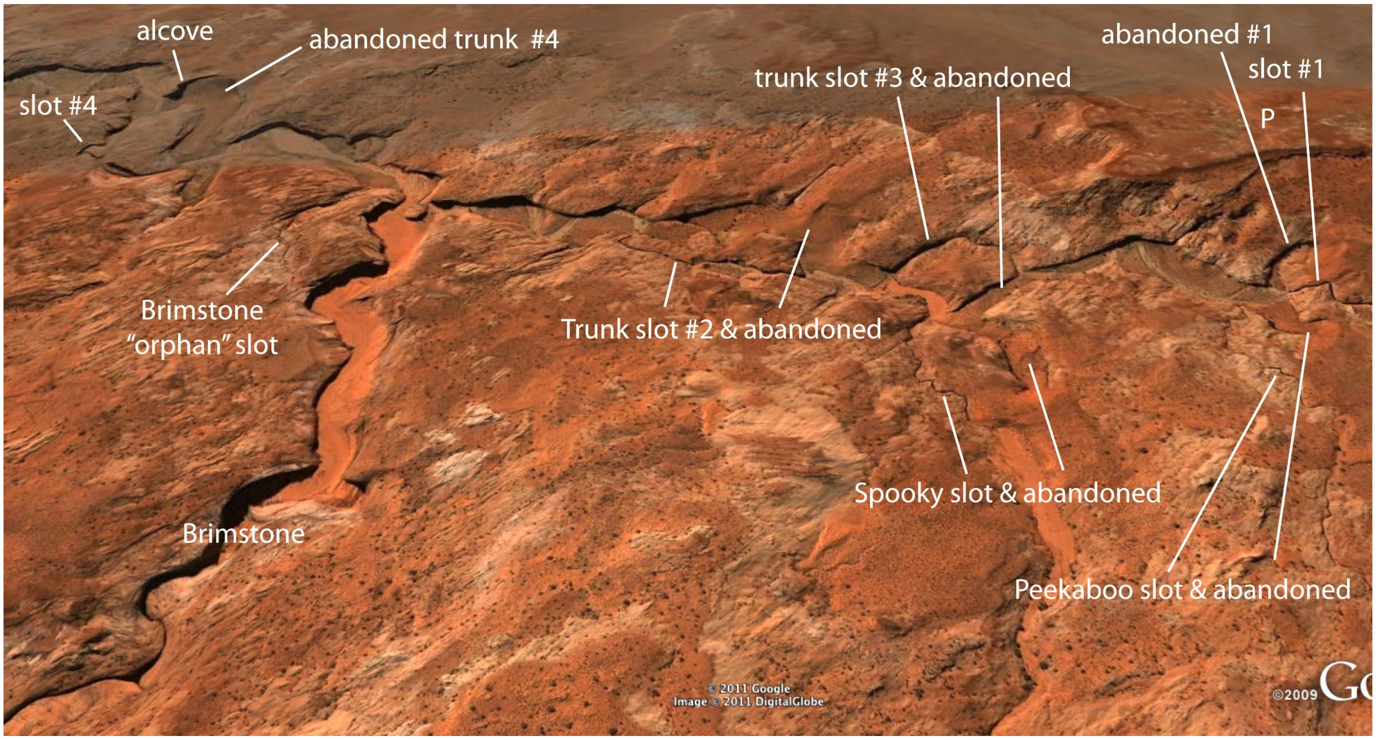

Figure 4. *Oblique Google Earth image looking north. "P" marks location of parking lot.*

Figure 5. *Alluvial fills and slot canyons. White arrows show people for scale. See figure 2 for locations. A. Northward view of thick alluvial fill of the trunk of Dry Fork #1 as seen from entry trail. People are about to enter trunk slot #1. B. Northward view of the alluvium-filled former course of Peekaboo and of Peekaboo Slot at its junction with Dry Fork.*

important things: (1) the slot canyons formed during episodes of rapid down-cutting by Dry Fork into its own thick, sandy alluvium; and (2) filling of the broad canyons could have resulted from a Pleistocene increase in landslides and debris flows in the steep tributaries that drain the Straight Cliffs escarpment (figure 6). His radiocarbon dates showed that the most recent episode of canyon filling (alluviation) in Dry Fork and nearby Big Hollow is Holocene, and began about 2500 years ago and ended prior to 730 years ago (Williams, 1984; Boison and Patton, 1985). Alluvium that now lies as much as 10 meters above the modern channel floor records that episode.

Boison and Patton (1985) hypothesized that Dry Fork received less of the alluvium because it, unlike Big Hollow (figure 2A), did not receive landslide debris in recent (late Holocene) times. These geologists realized that Dry Fork, during an earlier episode of alluviation (too old for radiocarbon dating), had filled to a much greater depth than 10 meters. In this preliminary report of our work at Dry Fork, we present optically stimulated luminescence (OSL) ages from alluvium that now lies as much as 40 meters above the floor of Dry Fork, and we tentatively hypothesize that, although some of alluvium may have been sourced from Pleistocene landslides, much of the ancient alluvium is

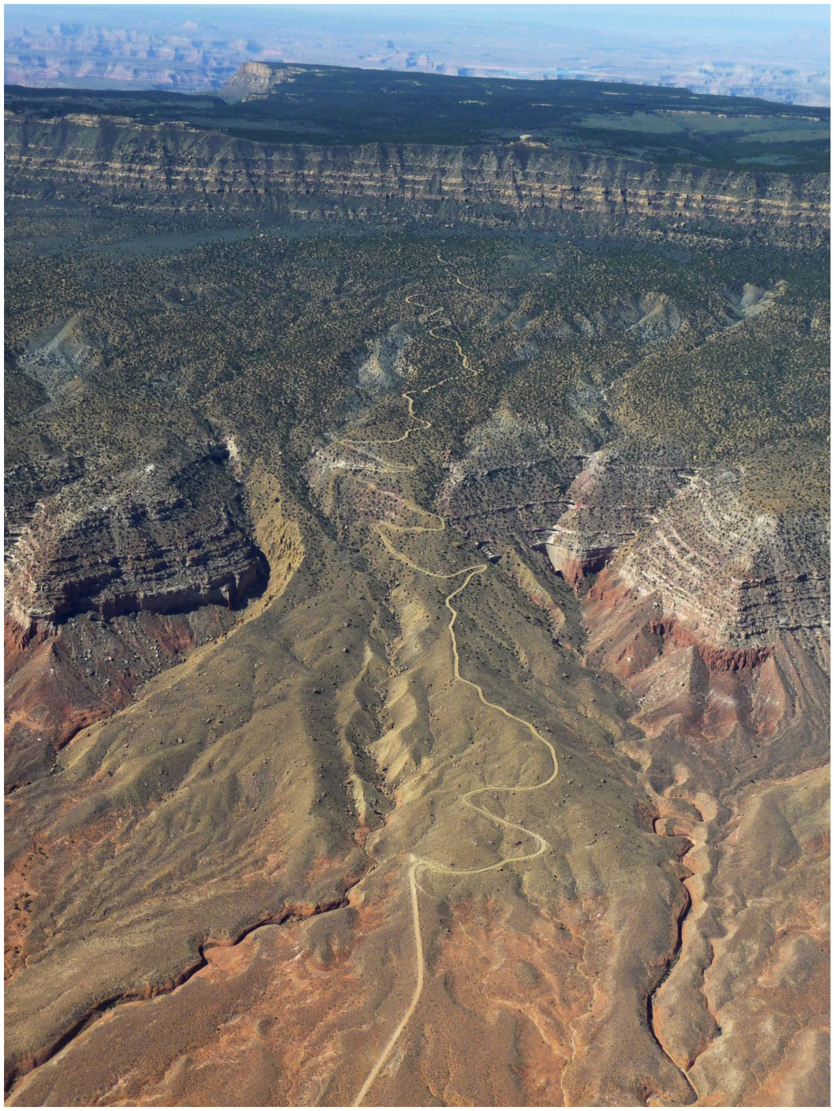

Figure 6. *Sooner Slide, a Holocene landslide at the base of the Straight Cliffs escarpment. See figure 2 for location. Photo by Jon Mason and Jodi Norris.*

likely composed of sediment that was sorted during wind transport before it entered the headwaters of Dry Fork. We think this sand was ultimately derived from Jurassic eolian sandstones (the Navajo Sandstone and, possibly, the Entrada Formation). It may have been blown directly into streams or reworked from Pleistocene dunes by streams. Alternatively, the streams may have swept the sand from weathered bedrock. Evaluating these possibilities requires further field and laboratory study.

ALLUVIAL FILL

Williams (1984) mapped the largest expanses of Dry Fork alluvium, but there are also many small, unmapped exposures. For OSL dating, we sampled alluvium at eleven localities (figure 2). At many sites, a mantle of wind-blown sand covers the alluvium (figures 3, 7B). At all but two of the exposures, alluvium is dominated by fine to medium sand, and bedding is very poorly developed. In an alcove at the southeast corner of our study area (sites 3338 and 3340), the alluvium is composed of alternating beds of silt and sand (figures 8A, B). Angular rockfall debris from the overhanging cliff is present in the alluvium at this site. At sampling site 3204 (figure 8C), we found conglomerate with clasts up to 15 centimeters in diameter in erosive contact with the much finer, better-sorted alluvium.

Rooted plants may have destroyed much of the original bedding as the alluvium was accumulating. Ancient roots preserved by calcite cement (rhizoliths) are present within the upper portions of the alluvium. Rhizoliths up to 1 centimeter in diameter are present within a paleosol at the top surface of the alluvium, and rhizolith fragments locally form surface lags. Although wind-blown sand is widespread today on both uplands and within canyons (figures 2, 8C), we found no sedimentary structures (wind-ripple lamination, grainflows) indicating ancient eolian deposition within the alluvium. Modern dunes are being actively reworked by streams in the study area, especially those like Peekaboo, Spooky, and Brimstone (figure 9C) that enter Dry Fork from the north.

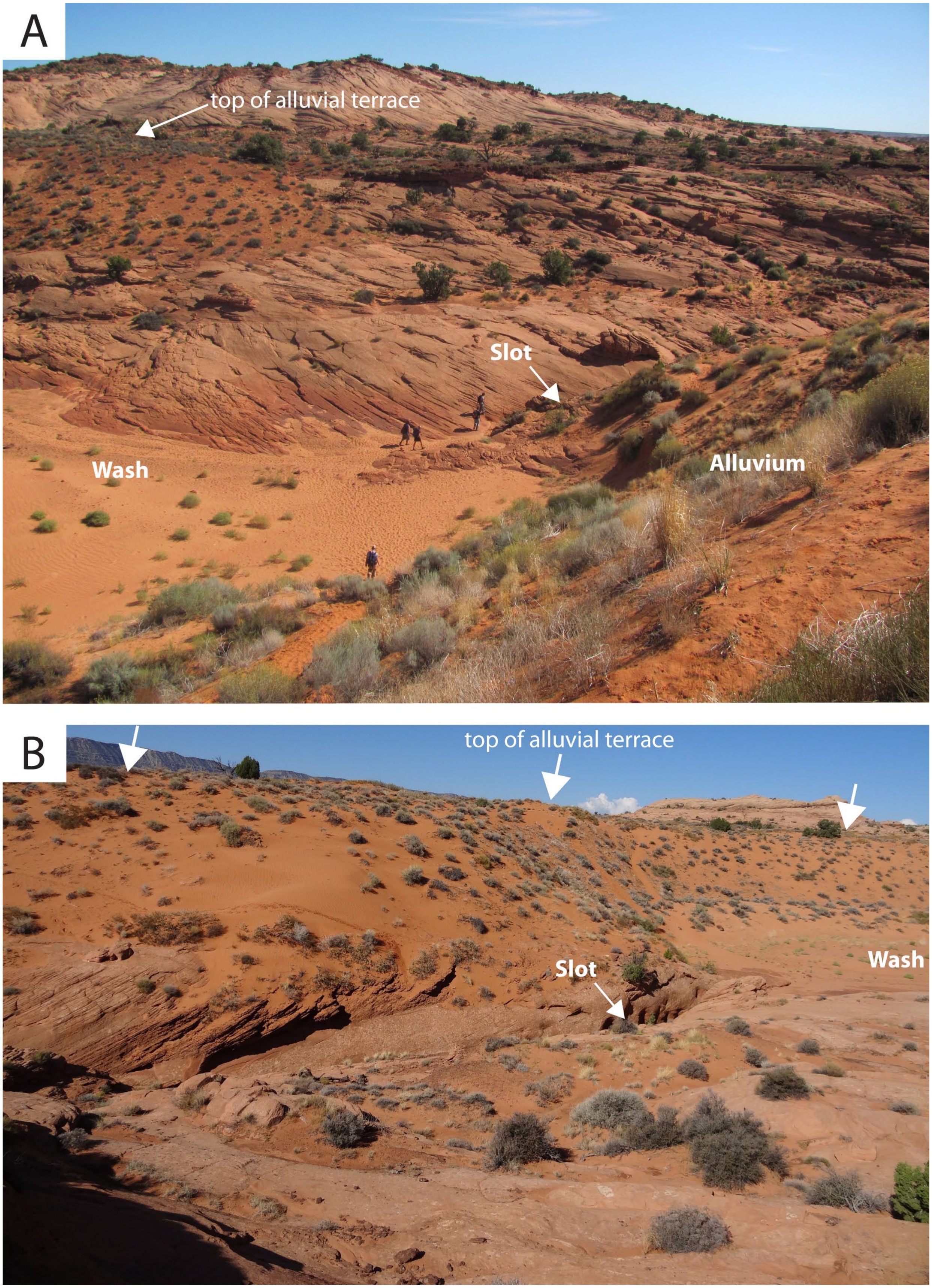

***Figure 7.** Upper entrance to Spooky Slot. **A.** View looking east. Flow in wash is left to right; people are about to enter slot canyon. Slope on right is alluvium with thin mantle of windblown sand. **B.** View looking west. Flow in wash (and slot) is right to left.*

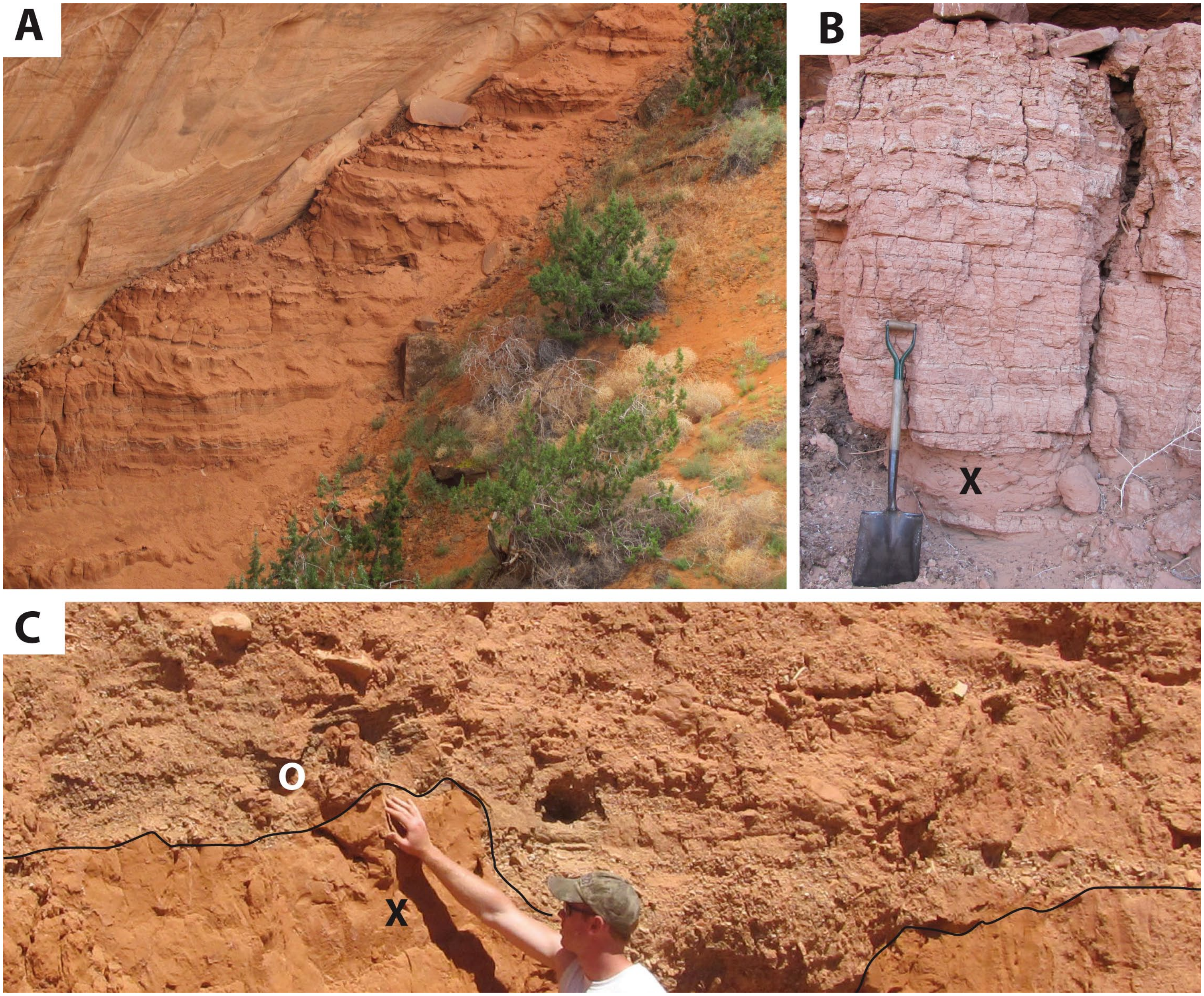

Figure 8. A. *Thick sequence of interbedded silt and sand in an alcove near the mouth of trunk slot #4.* ***B.*** *Close-up of silty beds near base of sequence. OSL sample 3340 (46.8 ka) was taken at "X."* ***C.*** *Alluvium at sample site 3099-3204. Well-sorted sand (3099) at "X" returned an OSL age of ~42.1 ka; sample in coarser material at "O" (3204) returned an age of ~39.8 ka. Note erosive contact.*

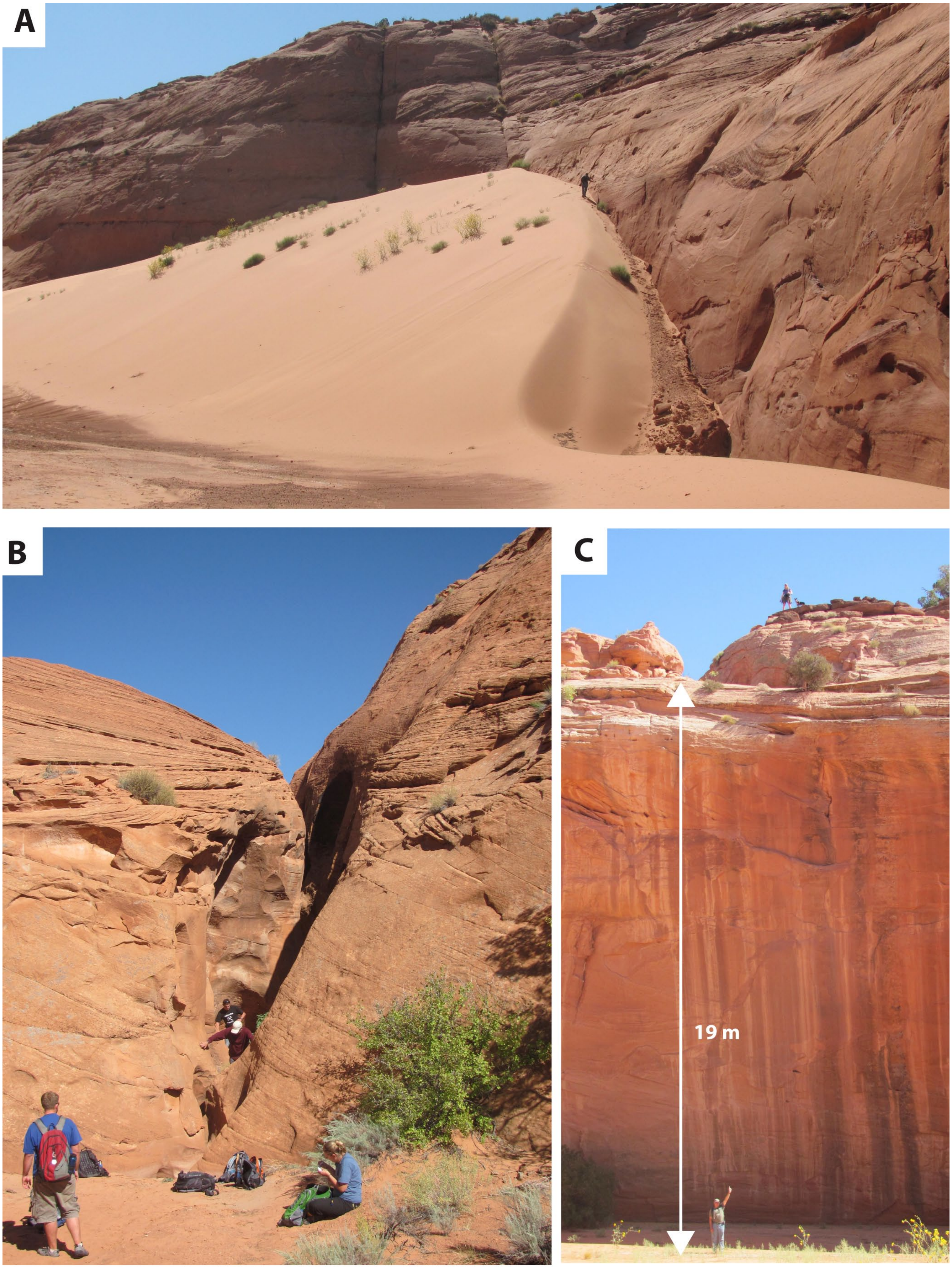

Figure 9. *Brimstone Canyon and its "orphan" slot.* ***A.*** *Dune sand near the mouth of Brimstone Canyon. Person near dune crest for scale.* ***B.*** *Mouth of the slot at its confluence with Dry Fork.* ***C.*** *Head of the slot canyon is at tip of upper arrow, 19 meters above the floor of Brimstone Wash. Stream incised some of its alluvial fill and then cut the slot before abandoning the slot when it overflowed its (west) alluvial bank and reoccupied the broad canyon. It then rapidly excavated the remaining 19 meters of fill in that canyon, leaving the orphan slot high, dry, and open.*

OSL SAMPLE PREPARATION/DOSE-RATE DETERMINATION

Sample preparation was carried out under amber-light conditions. Samples were wet sieved to extract the 90-150-micron fraction, and then treated with hydrochloric acid (HCl) to remove carbonates and with hydrogen peroxide to remove organics. Quartz and feldspar grains were extracted by flotation using a 2.7 grams per cubic centimeter sodium polytungstate solution, then treated for 75 minutes in 48% hyrdrofluoric acid, followed by 30 minutes in 47% HCl. The sample was then resieved and the 90-micron fraction discarded to remove residual feldspar grains. The etched quartz grains were mounted on the innermost 2 millimeters or 5 millimeters of 1-centimeter-diameter aluminum disks using Silkospray.

Chemical analyses were carried out using a high-resolution gamma spectrometer. Dose-rates were calculated using the method of Adamiec and Aitken (1998). The cosmic contribution to the dose-rate was determined using the techniques of Prescott and Hutton (1994).

OPTICAL MEASUREMENTS

Optically stimulated luminescence analyses were carried out on Riso Automated OSL Dating System Models TL/OSL-DA-15B/C and TL/OSL-DA-20, equipped with blue and infrared diodes, using the Single Aliquot Regenerative Dose (SAR) technique (Murray and Wintle, 2000). Early background subtraction (Ballarini and others, 2007; Cunningham and Wallinga, 2010) was used. Preheat and cutheat temperatures of 200°C/10s and 180°C/0s (young samples) and 240°C/10s and 220°C/0s (old samples) were selected based upon preheat plateau tests between 180º and 280ºC. Pulsed irradiation (Bailey, 2004; Bailey and others, 2005) was used to apply the regenerative doses to the oldest samples; a 280°C/40s blue diode shinedown was used at the end of each SAR cycle for these old samples (Murray and Wintle, 2003). Dose-recovery and thermal transfer tests were conducted (Murray and Wintle, 2003). Growth curves were examined to determine whether the samples were below saturation ($D/D_o < 2$; Wintle and Murray, 2006). Optical ages are based upon a minimum of 50 aliquots (Rodnight, 2008). Individual aliquots were monitored for insufficient count-rate, poor quality fits (i.e. large error in the equivalent dose, D_e), poor recycling ratio, strong medium versus fast component (Durcan and Duller, 2011), and detectable feldspar. Aliquots deemed unacceptable based upon these criteria were discarded from the data set prior to averaging. Calculation of sample D_e values was carried out using the Central Age Model (Galbraith and others, 1999) unless the De distribution (asymmetric distribution; decision table of Bailey and Arnold, 2006) indicated that the Minimum Age Model (Galbraith and others, 1999) was more appropriate.

RESULTS: TIMING OF ALLUVIATION

Eleven samples returned Pleistocene ages greater than 30 ka; the remaining 3 three samples returned Holocene ages of less than 3500 years (table 1). The sample returning the oldest age (~54.8 ka; UNL#3097; figure 2) lies about 15 meters above the bed of Dry Fork, so alluviation clearly began well before this time. The two samples nearest the upper surface of a prominent alluvial terrace (~49.6 ka and ~48.3 ka; UNL#'s 2895 & 3098, respectively; figure 2) provide the most reliable estimate of when the earliest cycle of alluviation was complete. Because of its upstream, westerly position, it is difficult to assess the relationship of site 3099 (with an OSL age of 42.1 ka) to sites 2895 and 2896. The conglomerate that lies just above the erosional surface at sites 3099-3204 is the only alluvium clearly derived from the Straight Cliffs escarpment, and it returned an age of about 39.8 ka. Ages from superimposed bedded alluvium at the alcove site are approximately 46.8 ka (lowest; UNL#3340) and 41.6 ka (near the top, UNL#3338). These samples, as well as samples 2896 (~44.4 ka) and 3096 (35.0 ka), lie well below the elevation of the top of the alluvial terrace and could possibly reflect renewed deposition after partial incision of the earliest alluvial cycle, although we found no obvious field evidence of multiple generations of cut and fill.

DISCUSSION

Climate Change, Aggradation, and Erosion

Streams adjust their profiles to carry the sediment supply with the water available to them. A relative increase in the sediment supply causes a stream to aggrade (deposit sediment); an increase in stream discharge results in erosion (figure 10). Earth's constantly changing climate causes streams to undergo cycles in which they repeatedly cut and then fill their channels. In today's climate, maritime tropical air masses move northward into the Colorado Plateau region in the late summer and fall. Convective storms associated with the Arizona Monsoon bring heavy rainfall to the Colorado Plateau. These precipitation events create flood discharges that move huge volumes of sediment through the canyons. During the Late Pleistocene (prior to 12,000 years ago), the climate of the Colorado Plateau was cooler and wetter (Anderson and others, 2000). Paleoclimate reconstructions suggest that tropical air masses did not penetrate far enough north to reach the Colorado Plateau because a more southerly position of the jet stream blocked development of high pressure over the midcontinent, and heavier snow packs diminished summer heating. Glaciers formed on highest mountains and plateaus. Although the Kaiparowits Plateau and Straight Cliffs were not high enough to develop an ice cap, freeze-thaw cycles were likely much more numerous there. Today, relatively

Table 1. *Field and laboratory data, and OSL results.*

UNL #	Field #	Lat-Long	Elev.(ft) (approx)	Burial Depth (m)	H_2O (%)*	K_2O (%)	±	U (ppm)	±	Th (ppm)	±	Cosmic (Gy)	Dose Rate (Gy/ka)	D_e (Gy)	No. of Aliquots	Age (ka)
UNL2894	712A1			0.5	2.5	1.87	0.05	1.21	0.09	3.62	0.20	0.26	2.28±0.08	7.68±0.36	51	3.36±0.20
UNL2895	712A2	37.4802; 111.2198	4738	0.7	0.7	1.07	0.04	0.64	0.08	2.11	0.18	0.25	1.43±0.06	70.9±1.3	60	49.6±2.2
UNL2896	712B1	37.4827; 111.2182	4727	1.1	1.2	0.95	0.03	0.62	0.07	1.50	0.15	0.24	1.26±0.05	55.0±1.2	50	43.7±2.0
UNL3096	3 -23 #1	37.4773; 111.2077	4727	1	5.8	2.97	0.06	1.75	0.11	6.20	0.28	0.27	3.36±0.12	117.6±2.0	55	35.0±1.4
UNL3097	3 -23 #2	37.4775; 111.2073	4666	1	3.6	1.85	0.05	0.75	0.08	2.63	0.18	0.27	2.08±0.07	114.0±2.9	53	54.8±2.5
UNL3098	3 -23 #3	37.4839; 111.2110	4780	1	0.4	1.07	0.03	0.57	0.06	1.63	0.13	0.27	1.97±0.07	67.9±1.6	51	48.3±2.1
UNL3099	3 -23 #4	37.4838; 111.2421	4823	1	0.5	1.70	0.04	0.59	0.07	2.30	0.17	0.27	1.41±0.06	82.9±1.6	58	42.1±1.8
UNL3203	5-13-11 #1,2,3	37.4838; 111.2421	4822	1	0.8	2.21	0.05	1.91	0.11	5.12	0.24	0.27	2.90±0.10	106.9±2.7	51	36.9±1.6
UNL3204	5-13-11 #4	37.4838; 111.2421	4824	1	0.7	2.42	0.05	1.31	0.09	3.79	0.22	0.27	2.84±0.10	113.2±2.1	50	39.8±1.6
UNL3338	7-31-11 #2	37.4689; 111.1888	4702	1	0.2	0.99	0.03	0.41	0.07	1.88	0.15	0.27	1.32±0.05	55.1±1.2	50	41.6±1.8
UNL3339	7-31-11 #3			1	0.7	1.41	0.04	0.75	0.07	2.38	0.17	0.27	1.78±0.06	2.73±0.31	54	1.53±0.18
								Minimum Age Model (Galbraith et al., 1999) =						0.87±0.10		0.49±0.06
UNL3340	7-31-11 #4	37.4691; 111.1886	4693	1	0.4	1.71	0.05	1.02	0.08	2.95	0.19	0.27	2.13±0.08	99.8±2.0	52	46.8±2.0
UNL3341	7-31-11 #1			1	0.4	1.15	0.03	0.46	0.06	1.65	0.14	0.27	1.44±0.05	1.57±0.17	60	1.09±0.13
								Minimum Age Model (Galbraith et al., 1999) =						0.70±0.09		0.48±0.06
UNL3415	9-25-11 #1	37.4718; 111.1897	4640	1	2.0	2.30	0.05	1.10	0.09	3.38	0.20	0.27	2.62±0.09	124.1±2.3	73	47.4±1.9

* In-situ Moisture Content
Error on De is 1 standard error
Error on age includes random and systematic errors calculated in quadrature

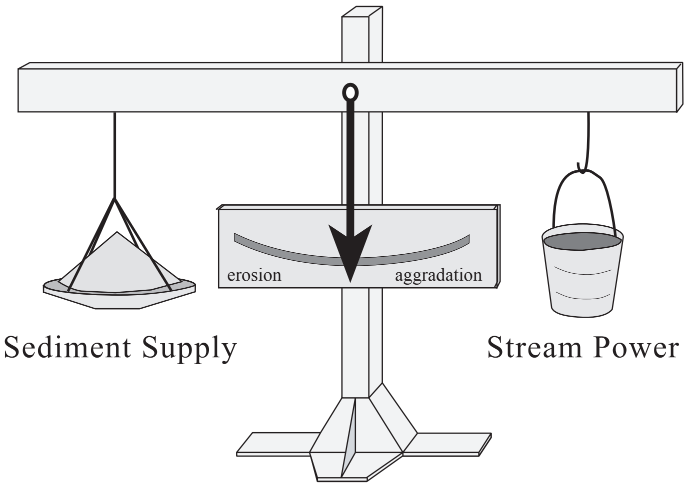

Figure 10. *Balance model for aggradation and incision of alluvial channels, emphasizing changes in the relationship between stream power and sediment supply. Channels aggrade when sediment supply exceeds transport capacity of the discharge regime, and incise when the reverse is true. Modified from Blum and Tornquist (2000).*

fresh landslides (figure 6) and debris flows are prominent features along this escarpment. Older landslides and debris flows are less prominent, but are considerably more widespread (figure 2A). It is possible that, between 50,000 and 60,000 years ago, increased weathering rates may have resulted in more sediment delivery to the headwaters of Dry Fork from the steep slopes of the Straight Cliffs escarpment. It is possible that alluviation in downstream reaches resulted from progressive redistribution of this sediment under the relatively wet and non-monsoonal conditions that were dominant prior to about 12,000 years ago.

We propose an alternate hypothesis for Dry Fork alluviation, however. Today, the Navajo Sandstone forms naked "slickrock" ridges and domes that are sandblasted and partially buried by wind-blown sand eroded from the bedrock (figure 3). We hypothesize that the alluvium that buried the broad canyons was dominantly derived from outcrops of the eolian Navajo Sandstone (and, possibly, the eolian Entrada Formation) and not from the marine and fluvial deposits exposed along the Straight Cliffs escarpment. Although we have not yet conducted a detailed stratigraphic analysis of sand and clay abundances and mineralogy, our field observations indicate that the alluvial deposits typically lack gravels, cobbles, and clay beds. The bulk of the alluvium is composed of fine to medium sand, suggesting less input from clay- and gravel-rich Straight Cliffs units and more input from units dominantly composed of sand. The ice-age climate may have been not only cooler and wetter, but also windier (Ellwein and others, 2011). We hypothesize that enhanced weathering led to release of more sand from weakly cemented sandstones. Sheet wash and wind then swept the sand grains from the bedrock. Strong winds moved sand into dunes and ultimately into streams, increasing their sediment supply. Because temperatures at the time were too cool for monsoonal storm activity, the small headwater streams (Etheredge and others, 2004) may not have been able to move all of the sand deposited in the channels of Dry Fork and its tributaries to the Escalante River (like they do today), leading to gradual aggradation over time and ultimately to canyons being filled with sand. Subsequent climate change may have brought increased flooding and an increase in time-averaged stream power to small drainage basins. This would have terminated the filling episode and initiated incision of the sediment fill and the cutting of slot canyons in new locations.

Epigenetic Gorges

The Dry Fork slot canyons are excellent examples of *epigenetic gorges* (figure 11). These form when stream channels get laterally displaced during episodes of alluviation and cut down into bedrock spurs or side-walls of their former canyon rather than simply excavating only unconsolidated deposits and re-inhabiting the previous canyon or valley. Ouimet and others (2008) provided an overview of epigenetic gorge formation with examples from different field settings and described multiple gorges cut into Navajo Sandstone along Trail Canyon in the Henry Mountains region of south-central Utah. Where epigenetic gorge formation is influenced by earlier aggradation from coarse landslide debris, stream action may preferentially winnow the fine sediment, generating a bed composed of the coarser cobbles and boulders. In this situation, stream erosion of bedrock may be more efficient than entrainment and transport of coarse sediment. In the Escalante and Henry Mountains regions, the Navajo Sandstone is strong enough to maintain high cliffs and a dramatic landscape, but it is nonetheless weak enough at the grain scale to be eroded efficiently during flow events. Monitoring of erosion and flooding by Johnson and others (2010) in the Henry Mountains showed that, in a particular steep channel reach in Navajo Sandstone, sustained snowmelt runoff deepened a bedrock inner-channel floor by 40 centimeters in a single month. Thus, it should not be surprising that downcutting may occur wherever a channel reach happens to be located, and that incision can occur in alluvium (maintaining an older stream channel) or bedrock (forming an epigenetic gorge). In the cases of Peekaboo Slot and Spooky Slot, Johnson and others (2010) suggested that valley aggradation diverted flow through local lows in the bedrock valley walls, which then led to a steeper local flow path over a sloping slickrock surface and rapid incision of much narrower channels. Finally, we note that Johnson and others (2010) suggested that Peekaboo Slot and Spooky Slot formed in response to sand dunes migrating and blocking the trunk streams. However, the subsequent field observations we present here indicate conclusively that alluvial aggradation, rather than eolian deposition, was the primary mechanism for stream aggradation.

Peekaboo, Spooky, and Brimstone Canyons share important aspects of their geologic history: all three were

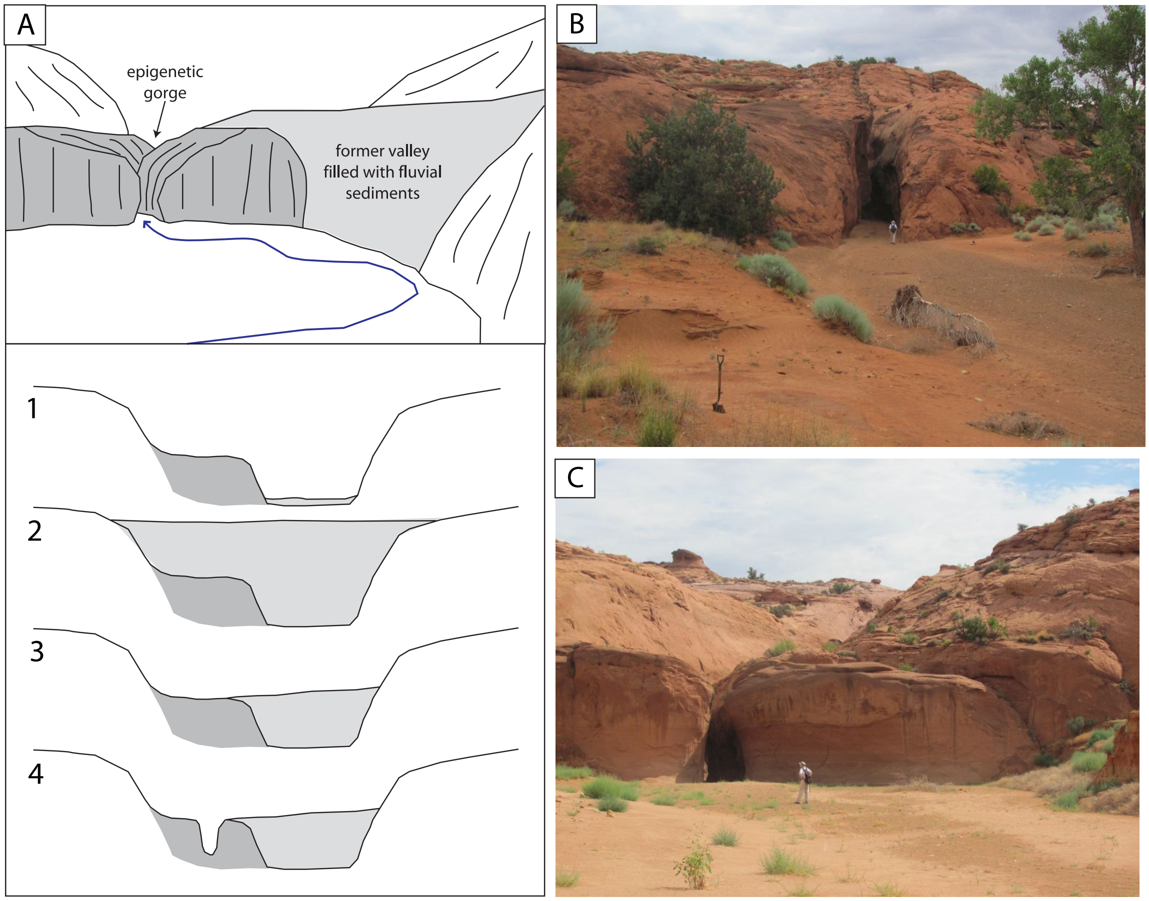

Figure 11. *Epigenetic gorges. See figure 2 for locations of photos. A. Stages of evolution of an epigenetic gorge (from Ouimet and others, 2008). B. Upstream entrance to trunk slot #3; C. Upstream entrance to trunk slot #4. In both B and C, the sediment-filled, broader canyon lies to the right (south) of the slot canyon.*

buried by alluvium, and, when removal of that alluvium was underway, all three developed slot canyons near their junctures with Dry Fork. Today, Peekaboo Slot and Spooky Slot continue to carry floodwaters; the lowermost portions of their buried canyons remain sand-filled. Brimstone's buried course, however, has been fully excavated (figure 9). The Brimstone slot canyon is an orphan—it is without a large catchment basin, and its head is atop a high cliff, overlooking Brimstone's broad canyon floor (figure 9). The stream that cut this slot escaped from its bedrock walls by overflowing its alluvial bank. It later excavated a course through the still-deeply-buried canyon, clearing out its fill and leaving the slot high and dry.

CONCLUSION

The slot canyons of Dry Fork are epigenetic gorges that developed during incision of thick alluvium that had buried older, broader canyons. We present new OSL dating of alluvium associated with slot-canyon incision, suggesting alluviation occurred around 50,000 years ago. We suggest hypothetical linkages between climate, flood intensity, sediment supply, and channel incision. Previous work on Colorado Plateau paleoclimate suggests that roughly 48,000 to 55,000 years ago, the climate was cool, wet, and windy. Cooler temperatures shut down the Arizona monsoon. Cooler, wetter conditions generally increase vegetative cover, thereby stabilizing dune deposits (Hugenholtz and Wolfe, 2005), but because a large portion of the Dry Fork drainage is a sea of bedrock, cooler and wetter conditions may not have greatly increased vegetative cover. We hypothesize that more frequent freeze-dry cycles enhanced weathering of the Navajo and Entrada Sandstone and stronger winds delivered more sand to headwater streams. Low-discharge streams laden with this sand buried canyons that had previously been cut by more powerful streams. When stream power increased relative to sediment supply, the stored sediment in Dry Fork was flushed downstream, and seven new slot canyons were cut.

ACKNOWLEDGMENTS

We thank Joe Mason, Walter Loope, and Jackie Huntoon for their helpful reviews of the paper. Derek Burgess, Jim Elder, Cindy Loope, and Shirley Yik assisted with fieldwork; Jon Mason, Jodi Norris, and Geoff Debenedetto helped with aerial photography. Kevin Phillips and Carolyn Shelton of Grand Staircase-Escalante National Monument provided encouragement and helpful suggestions throughout the duration of the study.

REFERENCES

Adamiec, G., and Aitken, M., 1998, Dose-rate conversion factors—update, *in* Aitken, M. J., editor, Introduction to Optical Dating: Oxford, Oxford University Press, Ancient TL, v. 16, p. 37-50.

Anderson, R.S., Betancourt, J.L., Mead, J.I., Hevly, R.H., and Adam, D.P., 2000, Middle- and late-Wisconsin paleobotanic and paleoclimatic records from the southern Colorado Plateau, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 155, p. 31-57.

Bailey, R.M., 2004, Paper 1—simulation of dose absorption in quartz over geological timescales and its implications for the precision and accuracy of optical dating: Radiation Measurements, v. 38, p. 299-310.

Bailey, R.M., Armitage, S.J., and Stokes, S., 2005, An investigation of pulsed-irradiation regeneration of quartz OSL and its implications for the precision and accuracy of optical dating (Paper II): Radiation Measurements, v. 39, p. 347-359.

Bailey, R.M., and Arnold, L.J., 2006, Statistical modeling of single grain quartz D_e distributions and an assessment of procedures for estimating burial dose: Quaternary Science Reviews, v. 25, p. 2475-2502.

Ballarini, M., Wallinga, J., Wintle, A.G., and Bos, A.J.J., 2007, A modified SAR protocol for optical dating of individual grains from young quartz samples: Radiation Measurements, v. 42, p. 360-369.

Blum, M.D., and Tornquist, T.E., 2000, Fluvial responses to climate and sea-level change—a review and look forward: Sedimentology, v. 47 (Supplement 1), p. 2-48.

Boison, P.J., and Patton, P.C., 1985, Sediment storage and terrace formation in Coyote Gulch basin, south-central Utah: Geology, v. 13, p. 31-34.

Cunningham, A.C., and Wallinga, J., 2010, Selection of integration time intervals for quartz OSL decay curves: Quaternary Geochronology, v. 5, p. 657-666.

Durcan, J.A., and Duller, G.A.T., 2011, The fast ratio—a rapid measure for testing the dominance of the fast component in the initial OSL signal from quartz: Radiation Measurements, v. 46, p.1065-1072.

Ellwein, A.L., Mahan, S.A., and McFadden, L.D., 2011, New optically stimulated luminescence ages provide evidence of MIS3 and MIS2 eolian activity on Black Mesa, northeastern Arizona, U.S.A.: Quaternary Research, v. 75, p. 395-398.

Etheredge, D., Gutzler, D.S., and Passaglia, F.J., 2004, Geomorphic response to seasonal variations in rainfall in the Southwest United States: Geological Society of America Bulletin, v. 116, p. 606-618.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., and Olley, J.M., 1999, Optical dating of single and multiple grains of quartz from Jinmium Rock Shelter, Northern Australia—part I, experimental design and statistical models: Archaeometry, v. 41, p. 339-364.

Hugenholtz, C.H., and Wolfe, S.A., 2005, Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains: Geomorphology, v. 70, p. 53-70

Johnson, J.P.L., Whipple, K.X., and Sklar, L.S., 2010, Contrasting bedrock incision rates from snowmelt and flash floods in the Henry Mountains, Utah: Geological Society of America Bulletin, v. 122l, p. 1600-1615.

Murray, A.S., and Wintle, A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol: Radiation Measurements, v. 32, p. 57-73.

Murray, A.S., and Wintle, A.G., 2003, The single aliquot regenerative dose protocol—potential for improvements in reliability: Radiation Measurements, v. 37, p. 377-381.

Ouimet, W.B., Whipple, K.X., Crosby, B.T., Johnson, J.P., and Schildgen, T.F., 2008, Epigenetic gorges in fluvial landscapes: Earth Surface Processes and Landforms, v. 33, p. 1993-2009.

Prescott, J.R., and Hutton, J.T., 1994, Cosmic ray contributions to dose rates for luminescence and ESR dating—large depths and long-term time variations: Radiation Measurements, v. 23, p. 497-500.

Rodnight, H., 2008, How many equivalent dose values are needed to obtain a reproducible distribution?: Ancient TL, v. 26, p. 3-9.

Williams, V.S., 1984, Pedimentation versus debris-flow origin of plateau-side desert terraces in southern Utah: Journal of Geology, v. 92, p. 457-468.

Williams, V.S., 1985, Surficial geologic map of the Kaiparowits coal-basin area, Utah: United States Geological Survey Miscellaneous Investigations Series, Map I-1033-L, scale 1:125,000.

Wintle, A.G., and Murray, A.S., 2006, A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols: Radiation Measurements, v. 41, p. 369-391.

Wohl, E.E., Thompson, D.M., and Miller, A.J., 1999, Canyons with undulating walls: Geological Society of America Bulletin, v. 111, p. 949-959.